EMMA – an Eye-Movement Measurement and Analysis System

Steven R. Muir[1], Michael R. MacAskill[2], David. Herron[1], Hansjerg Goelz[1], Richard D. Jones[1,2], Tim J. Anderson[2,3]
[1] Department of Medical Physics & Bioengineering, Christchurch Hospital, Christchurch, New Zealand
[2] Department of Medicine, Christchurch School of Medicine, University of Otago, Christchurch, New Zealand
[3] Department of Neurology, Christchurch Hospital, Christchurch, New Zealand

***Abstract* – A system has been developed for stimulation and measurement of a wide range of eye movements. Eye movements are stimulated with an LED bar or a video projector under the control of a PC. The eye movements are measured using a scleral reflection technique, and sampled and stored on a PC. Eleven tests have been developed to measure saccadic and smooth pursuit eye movements. A variety of tools have been developed to assist in the analysis of the data. Several research studies have ably demonstrated the utility and versatility of the system.**

***Keywords* – Eye movements, saccades**

I. INTRODUCTION

An Eye-Movement Measurement and Analysis (EMMA) system has been developed for the stimulation, measurement, recording and analysis of a wide variety of horizontal and vertical eye movements.

II. SYSTEM HARDWARE

EMMA consists of an IRIS instrument, two PCs, LED bar, colour video projector, and multi-tone audio generator (Fig. 1). The IRIS instrument (Skalar Medical, The Netherlands) uses arrays of infra-red LEDs and detectors to determine the position of the eye by comparing the amount of IR light reflected from the sclera on each side of the eye [1]. Accuracy is ±0.5° and range is linear up to ±20°. The two outputs of the IRIS are sampled at 200 Hz by the main PC. The data is saved to hard disk for later analysis. The main PC also controls stimuli generated on an LED bar – a curved bar containing 8-mm red LEDs at 5° intervals up to ±35°. A second PC, connected to the main PC via a parallel port link, is used to display a target on a screen (1160 by 1540 mm) using a colour video projector. A multi-tone audio generator can generate tones up to 10 kHz through either an external speaker or headphones. A typical tone is 50 ms, 1200 Hz. There is also a facility to generate variable-volume white noise on one channel of the headphones while directing a tone to the other ear. A 'bite bar', consisting of a wooden tongue depressor wrapped in wax, is used to hold the subject's head still during the tests, at a distance of 1.5 m from the LED bar or 1.7 m from the video screen. The subject is seated in a chair, which is raised or lowered so that the subject's eyes are at the same height as the stimulus.

III. SOFTWARE

The EMMA software is written in Modula-2 and runs under a DOS operating system. The software can be broadly divided into file handling, eye-movement tests and data analysis.

IV. CALIBRATION

Calibration of the IRIS instrument for saccadic tests is achieved by asking the subject to fixate at 0°, then to fixate alternately between ±15°. The sensors are adjusted so the

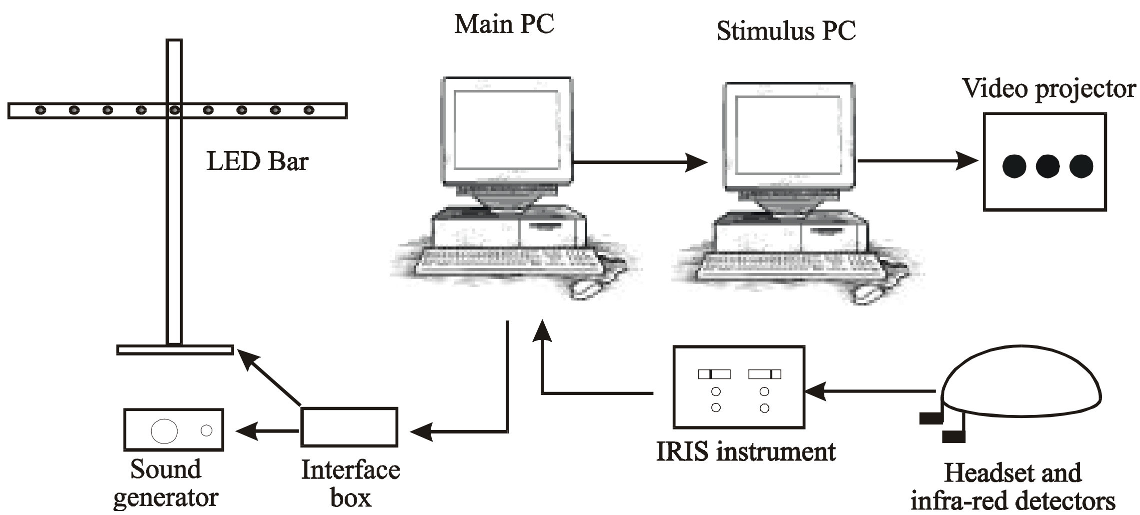

Fig. 1. EMMA system block diagram

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recorded eye movements match the actual eye movements. Calibration for a smooth pursuit test is achieved by asking the subject to follow a sinusoidal target ranging ±20°. A display of the eye position versus stimulus position allows the operator to adjust the sensors until a straight diagonal line is viewed on the monitor, i.e., the eye and stimulus positions are the same.

The IRIS instrument is very sensitive to small changes in sensor position due to movement of the headset. The result is a zero drift or change in gain occurring during a test. Software has been developed to correct for this based on known eye positions during the test and the use of linear regression to calculate the offset and gain factor before analysis of the test.

V. EYE-MOVEMENT TESTS

The following tests have been developed in the EMMA system. Tests which have random positions and times use pre-generated data which is saved in a default file so that the test can be precisely replicated with different subjects. A real-time display of eye position is provided on the main PC monitor during tests.

A. Saccadic tests

Self paced **–** Subject moves eyes between two continuously illuminated LEDs at ±15° as frequently as they can within a set time period.

Predictive **–** Subject moves eyes between two continuously illuminated LEDs at ±15° in synchronism with a tone at a constant repeat rate (typically 1.0 Hz).

Reflexive **–** Subject moves eyes to follow LEDs illuminated at random positions (up to ±15°) and random time interval (500–3000 ms). A tone is given when the LED position changes.

Remembered **–** While subject maintains fixation on an illuminated LED, a second LED is flashed at another random angle (up to ±15°) for 400 ms. After a variable time (1–3 s) a tone is given and the subject must move their eyes to where they remember the flash to have occurred. After a set time (typically 2 s), the LED in the position where they should have been fixating is illuminated. After another set time the process is repeated.

Sequence **–** Subject is asked to follow a sequence of LED positions (up to ±15°, typically 3–4 positions) at varying intervals (500–3000 ms) which is repeated several times (typically 4 times). The auditory stimulus of the first position in the sequence is lower (1200 Hz) than that of subsequent positions (1700 Hz) so the subject can become synchronised more easily. On the *n*th time the subject must repeat the sequence without the visual and auditory cues, attempting to maintain the position and timing of the practice stimulus.

Visual reaction time **–** Subject fixates on the rightmost of two LEDs which are continuously illuminated (±15°). After a random interval (500–3000 ms), this LED is flashed off (50 ms) and the subject moves their eyes as quickly as possible to the left LED. The process is repeated in the opposite direction.

Auditory reaction time **–** Subject moves eyes between two continuously illuminated LEDs (±15°) when an auditory tone (50 ms, 1200 Hz) is given at random intervals (500–3000 ms).

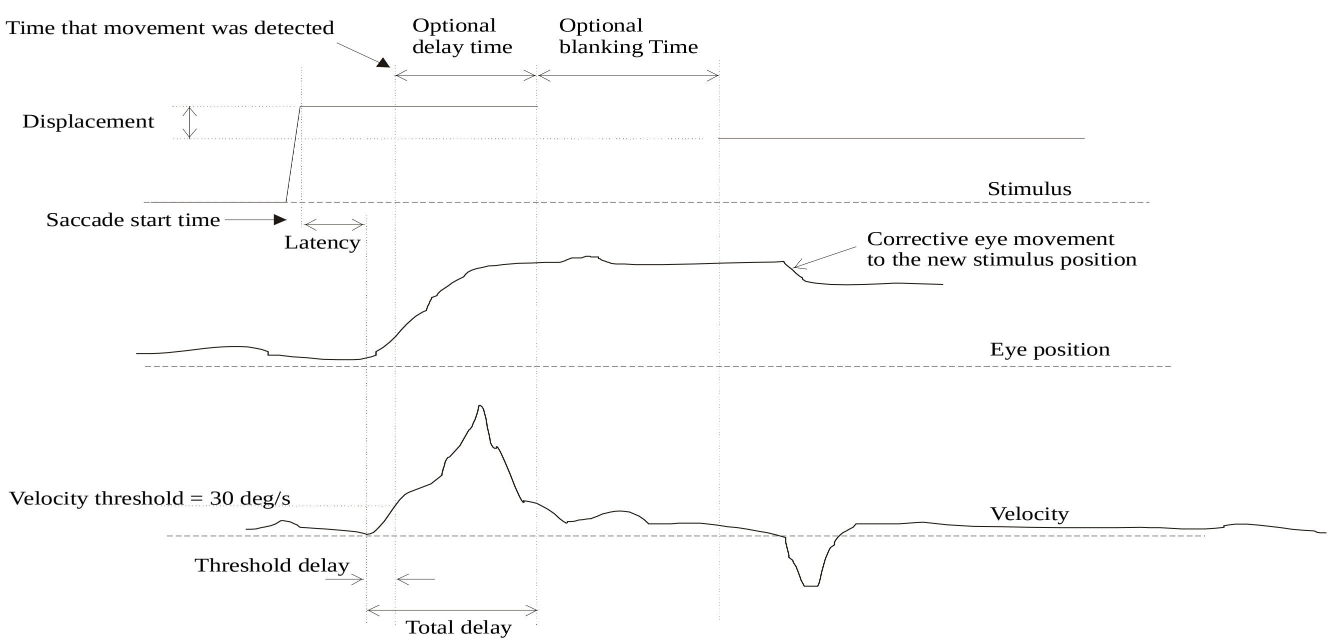

Fig. 2. Stimulus and eye movements in a reflexive displacement test

Reflexive displacement – A small square target (20 mm) of variable colour is superimposed onto a background image (typically a monotone colour or light blue marbled) and moves abruptly at random times (500–3000 s) to random positions (up to ±15° horizontally and up to ±10° vertically if required) (Fig. 2). At a set time after the subject's eyes commence movement towards the target, the target (and the entire background if desired) is displaced slightly (0.5–8.0°). Displacement may be either horizontal or vertical, and in the same or opposite direction to eye movement. Due to intrasaccadic visual suppression, the subject will not usually see the image move if the displacement is <12% of the primary step [2]. The subject may be asked to provide feedback of any detected displacement by pressing a key on a keyboard. There is a facility to include a delay between the initiation of eye movement and the displacement of the target, and also to blank the target for a brief time (0–1000 ms) before it is shown at the displaced position.

Remembered displacement – Similar to the remembered test except that when the target reappears after the subject moves their eyes it is at a slightly displaced position (0.5–8.0°).

B. Smooth pursuit tests

Sinusoidal – Subject aims to follow a yellow hollow circle with cross hairs (90 mm total diameter, edge thickness 10 mm) which moves horizontally (±20°) on the screen with a sinusoidal velocity. The maximum velocity of the sinusoid can be varied from 10 to 80°/s.

Random – Subject aims to follow a yellow circle with cross hairs (90 mm total diameter, edge thickness 10 mm) which moves horizontally on the screen in a random pattern (up to ±20°). The random waveform is generated by using the 'sum of sinusoids' method, which, in this case, is the addition of 21 harmonically related sinusoids of random phase with fundamental frequency of 0.007 Hz. The resulting target has a maximum velocity of 88°/s and average velocity of 27°/s for a maximum stimulus angle of ±20°.

VI. EYE-MOVEMENT ANALYSIS

A. Saccades

Analysis of saccadic tests is achieved using cursors placed either manually or automatically on a saccade. The gain, latency and maximum velocity are measured along with additional parameters specific to each test (Fig. 3).

B. Sequences

The sequence test has further measures calculated for each sequence of saccades (Fig. 4) such as:

- Absolute Time Index (ATI) – total time taken to complete the sequence relative to that of the target sequence, showing whether a subject speeds up or slows down without the stimulus.
- Inter-Response Index (IRI) – a measure of how well a subject has kept the rhythm during a sequence, i.e., whether the time between each saccade in a sequence is correct relative to the total time.

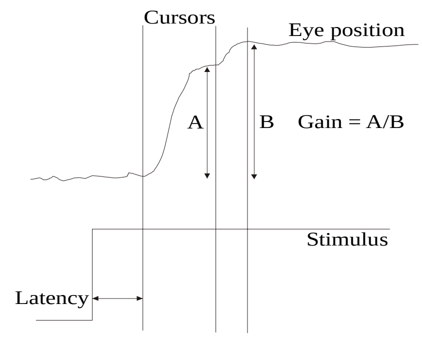

Fig. 3. Measuring the gain and latency of a saccade.

C. Smooth Pursuit

Before making calculations on a smooth pursuit test, eye blinks are manually or automatically detected and replaced by a straight-line interpolation. Measures on a smooth pursuit test include:

- Average peak velocity gain (for a sinusoidal target) – ratio of average of the subject's peak velocities to the target's maximum velocity.
- Mean absolute error – average of the absolute error between the subject's eye position and the stimulus, over all samples in the recording.
- Gain and lag – determined via cross correlation function.

VII. CLINICAL AND NORMAL STUDIES

The utility of the system has been ably demonstrated in a number of research studies on subjects with neurological conditions as well as in investigations of oculomotor and visual phenomena in normal subjects.

The system has also been utilised in a number of studies designed to look for and characterise oculomotor deficits in developmental stutterers [3], people with cerebellar disorders [4], and people with mild closed head injury [5].

The precision and accuracy of the recordings has been shown in several investigations. Small amplitude benign upbeat nystagmus, detectable by clinicians only on inspection by ophthalmoscopy, has been recorded and quantified using the EMMA system [6]. Another study required the accurate recording of the simultaneous velocities of both eyes during saccades. Internuclear ophthalmoplegia (INO) is a disorder, common in multiple sclerosis (MS), which results in the adducting eye having a slower velocity than the abducting eye. Subjects were categorised as having an INO if their ratio of abducting to adducting eye velocity exceeded the normal range. This objective diagnostic criterion was used in a signal detection study to assess the ability of neurologists and neurology registrars to detect INOs using the traditional clinical method [7]. There was a wide variation in the ability of those clinicians to accurately diagnose the condition.

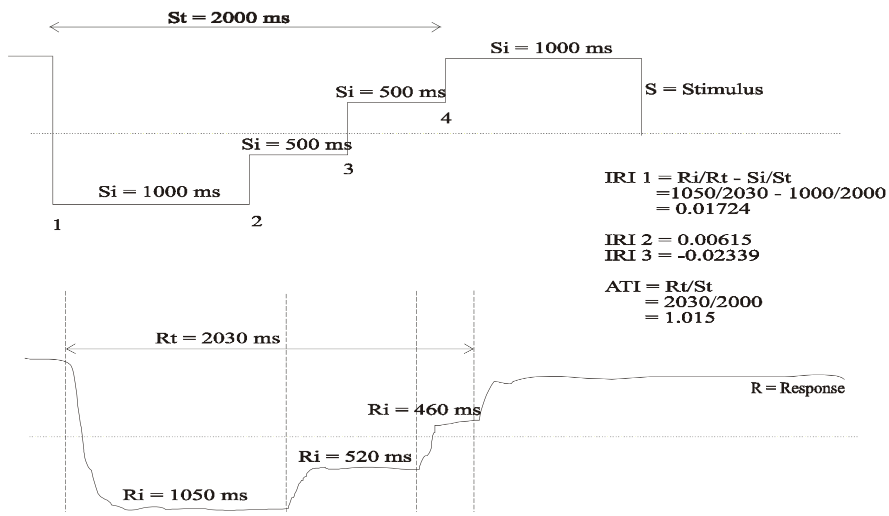

Fig. 4. Calculating IRI and ATI for a sequence test

Saccadic reaction times (latencies) are easier to measure accurately than are eye movement amplitude or velocity, with precision limited only by the sampling rate (generally 200 Hz). In one study, the latencies of MS subjects performing visually guided saccades were shown to be long relative to controls whereas their auditory-guided latencies were normal [8], confirming that the commonly observed long latency of MS saccades is due to visual delays rather than motor delays. The significant differences were of the order of only 20-30 ms.

The ability of the system to respond to saccades in real time and to change the visual display within the time course of a saccade has allowed us to study oculomotor and perceptual responses to intrasaccadic target displacements. People remain unaware of intrasaccadic target displacements if they are less than a certain size. We have been able to investigate a number of factors which influence the magnitude of the effect [9], [10]. Additionally, a person with pathologically slowed saccades was shown to be able to appropriately modify her saccades in-flight in response to intrasaccadic displacements of which she was not consciously aware [10].

VIII. CONCLUSION

The EMMA system allows a comprehensive range of eye movements to be tested and analysed with relative ease. The effectiveness of EMMA has been demonstrated in a wide variety of studies of normal and abnormal oculomotor function.

Further development of the system is continuing, with the addition of new tests and analysis techniques. A Windows–based version of the software is planned.

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